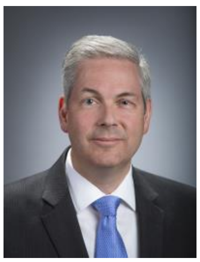
47TH TURBOMACHINERY & 34TH PUMP SYMPOSIA
HOUSTON, TEXAS | SEPTEMBER 17-20, 2018
GEORGE R. BROWN CONVENTION CENTER

GAS TURBINE EMISSIONS IMPROVEMENTS BY ADVANCES IN DESIGN, ANALYSIS, MATERIALS, MANUFACTURING, AND CONTROL TECHNOLOGY

David M. Stansel
Combustion Program Manager
Solar Turbines
San Diego, California, USA



David M. Stansel is combustion program manager at Solar Turbines, in San Diego, California. His organization is responsible for the development and improvement of combustion systems for all the gas turbine products at Solar Turbines. Since joining Solar in 2000, he has worked on a variety of Dry Low Emissions combustion systems, with increasing levels of responsibility, including twelve years as group manager for the SoLoNOx combustion group. Prior to joining Solar, he worked at Rolls Royce/Allison in Indianapolis for seven years. He received a B.S. degree (Mechanical Engineering) from Brigham Young University and an M.S degree (Mechanical Engineering) from Purdue.

ABSTRACT
This tutorial provides a general overview of the state of gas turbine combustion technology. Fundamental considerations for key pollutants are discussed along with techniques to control them. Since the commercial introduction of lean combustion in the early 1990s, it has become the preferred technology to minimize NOx emissions from a gas turbine, while Selective Catalytic Reduction (SCR) has remained a necessary technique to further reduce NOx emissions in some regulated areas with poor air quality. Improved designs have been enabled by more capable analysis, manufacturing techniques, and materials. All of this is leading to lower emissions engines with greater fuel flexibility and durability. Traditional diffusion flame combustion systems generate NOx between 100 and 400 ppm on natural gas, while early DLE systems started at 42 ppm and are now capable of single digit NOx. The importance of fuel quality and fuel treatment is also discussed.

INTRODUCTION
Industrial gas turbines are used to generate electricity, drive pumps and compressors, and provide motive power for ships. At the heart of the industrial gas turbine, lies the combustion system. The major features of all gas turbine combustion systems are one or more combustors, fuel injectors, fuel supply, and an ignition system, as shown in figure 1.

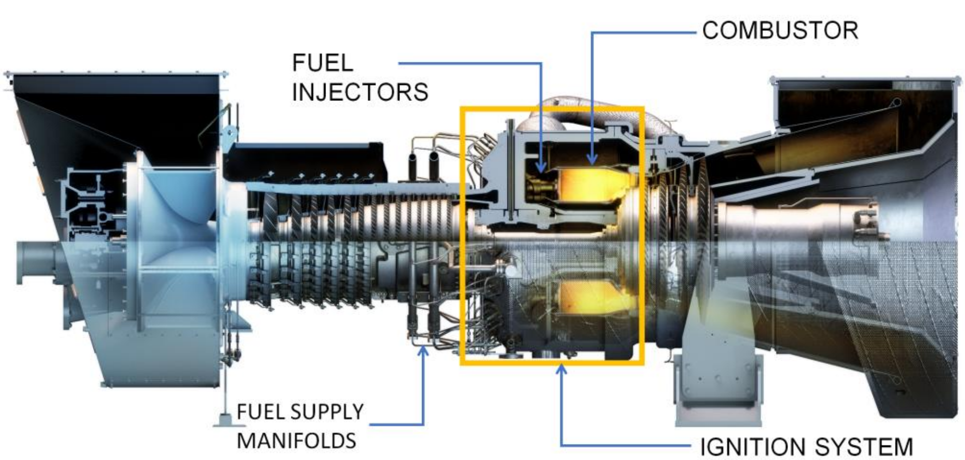


Figure 1. Major Components of an Industrial Gas Turbine Combustion System.

There are multiple design requirements on the combustion system, see figure 2. At its simplest, the combustion system converts all the chemical potential energy in the fuel to a rise in temperature of the working fluid (air). The remaining requirements reflect a compromise between performance, flexibility, durability, and cost. The various design features in any given combustion system are highly coupled and complex. This has led to industrial gas turbines with a wide variety of configurations and capabilities. But the industry has settled on two distinct combustion system types: conventional diffusion flam, and lean premixed or DLE (Dry Low Emissions). The focus of this tutorial is the design considerations and advancements of the DLE system.

Figure 2. Design Requirements and Considerations for a Gas Turbine Combustion System.

Figure 3 shows a comparison of a conventional (diffusion flame) combustion system and DLE. In the conventional system, fuel is injected into the combustor with very little air. The air comes in separately. Burning occurs at the interface between fuel and air where the local fuel/air ratio is near stoichiometric. This creates a stable, high temperature flame, in excess of 4000ºF (2500K). The DLE system seeks to lower the NOx, by lowering the flame temperature to 2900ºF (1860K) or less. A larger fuel injector is required to premix the fuel and air prior to burning. A larger combustor volume is also required to allow sufficient time for complete combustion at the lower temperatures in a DLE system. While the conventional system only allocates 30% of the overall combustion air to come in through the fuel injectors, a DLE system uses 60% of the overall combustion air in the injectors to achieve the lower temperatures. By the time the balance of the air comes in through the combustor liner and mixes out, the same temperature is delivered to the turbine inlet.

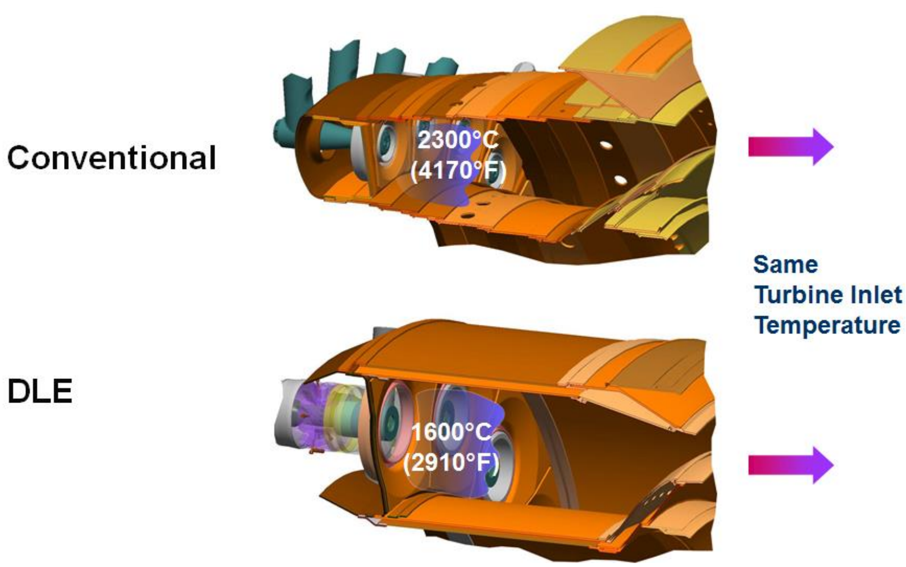


Figure 3. Conventional (Diffusion Flame) and DLE Combustion Systems. Note Larger Fuel Injectors and Liners for DLE.

FUNDAMENTALS OF EMISSIONS

When hydrocarbons are used as fuels, the result of complete combustion are carbon dioxide (CO2) and water (H2O). However, there are several undesirable products of combustion, which include NOx and products of incomplete combustion such as carbon monoxide (CO), unburned hydrocarbons and other volatile organic compounds, as well as particulate matter.

NOx Formation and Regulation

NO_x is a generic term for the oxides of nitrogen, NO and NO_2. All that is required to form NOx is to bring air to very high temperature, especially in the presence of radical species that are readily available during combustion. NOx is formed as NO in the flame zone of the combustor and partially oxidizes to NO2 downstream within the combustor. The split between NO and NO2 can be important for visible exhaust plumes, since it is the NO2 that gives the exhaust a brown hue.

NOx is an environmental concern for several reasons. When NOx and volatile organic compounds react in the presence of sunlight in the atmosphere, they form photochemical smog, a significant form of air pollution. The ground level ozone that is created can cause damage to lung tissue and a reduction in lung function. NO_2 gives smog its brown haze. NOx also contributes to acid rain, which can lead to deforestation, fish kills, and damage to buildings and monuments, especially those made of limestone or marble.

Emissions regulations have been applied to industrial gas turbines in the United States since the mid-1970s (Greenwood, 2000). The regulations are complex and vary depending on local air quality and the quantity of emissions from any given project. All natural gas fired combustion turbines in the U.S. must meet, at a minimum, the federal New Source Performance Standard (NSPS) of 15 ppm or 25 ppm NOx (parts per million volumetric, corrected to 15% O2 in the exhaust) depending on size of the turbine. There are other NSPS standards for non-natural gas gaseous fuels and liquid fuels. In addition, other federal and/or state/local regulations may require lower emissions levels of NOx and other pollutants. While NOx is the primary pollutant regulated from gas turbines, other criteria pollutants are also regulated including CO (carbon monoxide), VOC (volatile organic compounds), SO2 (sulfur dioxide), and PM10/2.5 (particulate matter). For federal permitting, projects in “attainment” areas, areas with clean air, emitting more than significant ton/year thresholds are required to meet Best Available Control Technology (BACT), which is considered the best technology that has been demonstrated as practical and economically viable. Today federal BACT levels for industrial gas turbines range from 9-25 ppm depending on the location, fuel, and other site-specific parameters. In “nonattainment” areas, areas with poorer air quality, the most stringent standards are applied - referred to as LAER (Lowest Achievable Emission Rate). Federal LAER requires the best control technology available, regardless of economic consequences, and currently ranges from 1.5-2.5 ppm NOx. Some states have their own versions of BACT and LAER emissions requirements. International regulations vary significantly and range from 9 to over 200 ppm NOx.

The primary mechanisms of combustion-produced NOx include Thermal NOx, Prompt NOx, and Fuel NOx.

Thermal NOx

Sometimes called Zeldovich NOx, after the Russian physicist who described the mechanisms in his 1939 doctoral dissertation. Thermal NOx only requires nitrogen in the air to combine with O and OH radicals, which are in abundant supply in a flame.

$$N2 + O \rightarrow NO + N$$
$$N + O2 \rightarrow NO + O$$
$$N + OH \rightarrow NO + H$$

The reactions are highly temperature dependent, so the hotter the combustion, the more NOx is formed. The NOx formation rate is also pressure and residence time dependent. Decreasing any of these three reduces the NOx, but the exponential dependence on temperature makes reducing combustion temperature the key strategy to low NOx combustion. Fortunately, the thermal NOx formation rates are relatively slow; equilibrium concentrations are never reached in practical combustion devices.

Prompt NOx

The presence of a second mechanism leading to NOx formation was first proposed by Charles Fenimore and was termed “prompt NOx” in 1971. When thermal and fuel NOx are eliminated, some NOx formation was still observed. Fenimore attributed this to the reaction of atmospheric nitrogen with combustion radicals occurring in the earliest stages of combustion.

$$CH' + N2 \rightarrow HCN + N'$$
$$N' + OH \rightarrow NO + H'$$
$$N' + O2 \rightarrow NO + O'$$
$$HCN + O2 \rightarrow NO + CO + H'$$

Because this mechanism is not significantly temperature dependent, it becomes more important when other NOx formation mechanisms have been suppressed. Prompt NOx cannot be practically quenched because the length scales are so small. So, prompt NOx must be lived with and focus is normally placed on suppressing the other two main NOx mechanisms.

Fuel NOx

When nitrogen is chemically bonded to the fuel, essentially all of it converts to NOx in the exhaust. While most gaseous fuels, such as natural gas, are free of fuel bound nitrogen, it is often found in liquid and solid fuels. Untreated fuel oil can contain over 1,000 ppm of fuel bound nitrogen, which can result in over 40 ppm NOx in the exhaust just from this mechanism. Sulfur found in liquid fuels can also lead to acid rain and can poison the catalysts used for emissions control in automobiles and other combustion sources. Fortunately, refinery processes that remove sulfur also remove fuel bound nitrogen. Ultra-Low Sulfur Diesel (ULSD), defined in ASTM D975 as containing less than 15 ppm sulfur, typically contains less than 10 ppm fuel bound nitrogen, which will add less than 1 ppm NOx to the exhaust. Low Sulfur Diesel (LSD) has less than 500 ppm sulfur and can add a few ppm NOx to the exhaust, while high sulfur diesel allows up to 5,000 ppm (0.5%) sulfur, accompanied by enough fuel bound nitrogen to produce an additional 50 ppm NOx, which is unacceptable in most areas where NOx is regulated.

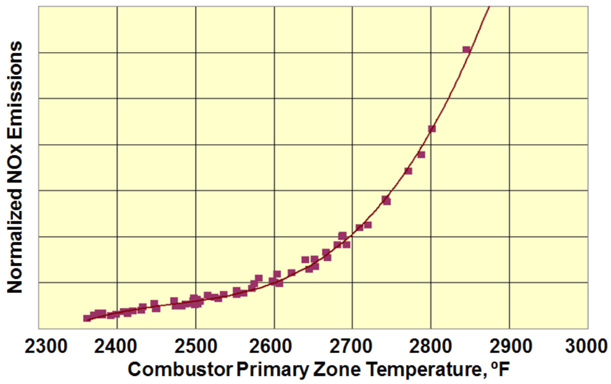


Figure 4. NOx is an Exponential Function of Tpz (Combustor Primary Zone Temperature).

NOx discussion

The combination of the above mechanisms results in an exponential relationship between NOx and combustion primary zone temperature (Tpz) as shown in figure 4. Lovett and Abuaf (1992) and Leonard and Stegmaier (1993) reported several key points for a lean premixed system.

- The best NOx is always achieved with perfect premixing of fuel and air.
- NOx emissions for well-mixed systems are independent of flameholder geometry
- A well-mixed flame is insensitive to pressure or inlet temperature. A diffusion flame is sensitive to both, leading to high pressure ratio engines having higher NOx than low pressure ratio machines. But a high pressure-ratio DLE system should be able to achieve the same NOx as a low pressure ratio machine.
- NOx for a well-mixed system is independent of residence time. So a DLE system can have a larger combustor liner without increasing NOx.

All the above conclusions are very fortunate and helpful in the design of a DLE system. Low NOx can simply be achieved by mixing well and holding a low Tpz. And low NOx is possible with any pressure ratio engine.

Practical DLE combustion systems make use of a pilot circuit to aid combustion stability, particularly at low loads as engine fuel demand reduces and temperatures drop. If the pilot is not also well-mixed, its NOx contribution will follow that of a diffusion flame system, with sensitivity to temperature, pressure, and residence time. For systems with diffusion or partially premixed pilots, the fraction of fuel to the pilot circuit must then be kept very low, typically less than 5% of the total fuel flow, to maintain low-emissions levels. At very low loads, where higher pilot may be required, NOx can be higher than at full load. In contrast, the diffusion flame combustor has highest NOx at the highest loads.

CO Formation

Both carbon monoxide (CO) and unburnt hydrocarbons (UHC) are regulated pollutants. Carbon monoxide is colorless, odorless and highly toxic. CO is also an ingredient in photochemical smog. Unburnt hydrocarbons represent any partially of fully unburnt hydrocarbon fuel. For natural gas fired gas turbines, the UHC in the exhaust is primarily methane (CH_4), the main constituent of natural gas. Methane is a powerful greenhouse gas, 28 times more potent than CO_2 over a100 year span, according to the Intergovernmental Panel on Climate Change (Myhre, et al., 2013).

When hydrocarbon fuels are completely combusted, the only products are water (H_2O) and carbon dioxide (CO_2). Even with greenhouse gas concerns for CO_2, the goal of the combustion engineer is to achieve complete combustion and maximize the conversion of fuel to CO_2. If the fuel undergoes partial combustion, unburnt hydrocarbons (UHC) and carbon monoxide (CO) result. CO is an intermediate product of combustion and the conversion of CO to CO_2 is relatively slow and temperature sensitive.

$$CO + OH \rightarrow CO_2 + H$$

If the reaction is quenched, CO will be elevated. So any cooling air or air leaks in a combustion system can lead to elevated levels of CO. Hence ensuring low CO comes down to two important elements.

- Ensuring the combustor is large enough for full combustion, especially at the lower temperature associated with low load
- Eliminating as much cooling air into the combustor as possible

Showing the NOx and CO emissions as a function of fuel/air ratio or flame temperature is insightful. Figure 5 shows that there is an optimum range of fuel/air ratio where NOx and CO are minimized. Higher temperatures lead to increased NOx while lower temperatures lead to increased CO. However, both curves can be improved. As discussed above, perfect premixing leads to the best (lowest) NOx curve. The CO curve can be improved by reducing the quenching of the CO burnout. Here, combustor volume and careful management of cooling air are the key.

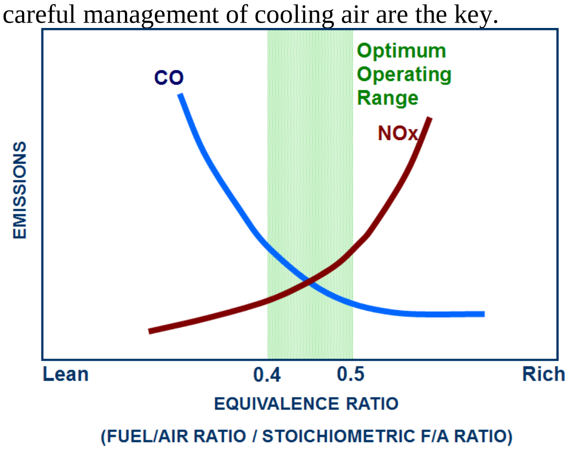


Figure 5. NOx and CO Emissions are Dependent on Fuel/Air Ratio (Temperature).

OPERATING RANGE

To make a combustion system useful for practical applications, it must be capable of operating over a wide range of ambient and load conditions, as well as with various fuels. In particular, DLE systems require careful design considerations.

Turndown / Lean Stability

Practical combustion systems must operate over a range of conditions. Because a gas turbine requires more fuel at full load than at idle, bulk temperature in the combustion system also varies through the load range. But a DLE combustion system, by its nature, has a very narrow operating range vs temperature. Figure 6 shows how a diffusion flame system operates very near the peak temperature and the stoichiometric fuel/air ratio (that ratio where all the fuel is consumed and there is no excess air). A DLE system operates lean to minimize flame temperature and NOx formation. However, there is a fuel air ratio where the process gets too lean to sustain stable combustion and the flame extinguishes. The condition is known as lean blowout (LBO) or lean extinction. Rumble or partial flameout can occur at conditions approaching lean extinction.

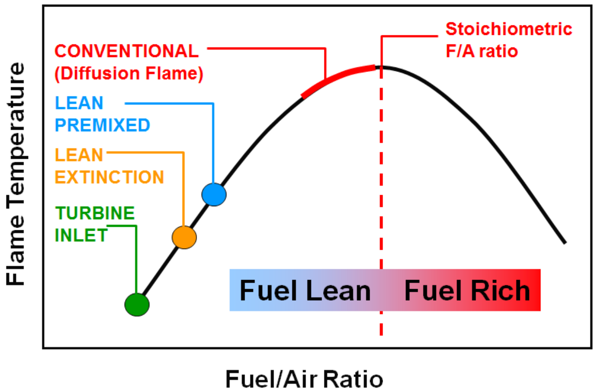


Figure 6. Effect of Fuel/Air Ratio on Flame Temperature. Operating Limits for a DLE System.

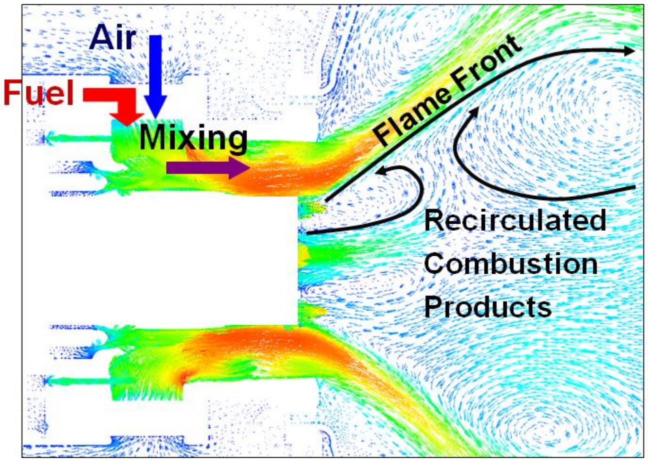


Figure 7. DLE Radial-Swirled Fuel Injector and Primary Zone Showing Total Velocity Vectors.

Choice of flameholder geometry or swirl angle exiting a fuel injector has a significant impact on lean stability. The flame speed (also called burning velocity) is dependent on combustion conditions (temperature, pressure, fuel/air ratio) and fuel composition. Because the flame speed is lower than the bulk velocity of flow exiting a fuel injector, the flow must be slowed to establish a stable flame. Most OEMs today employ swirling flow within the fuel injector, coupled with a sudden expansion at the injector exit, to induce vortex breakdown and flow recirculation. See figure 7. Once ignited, combustion is established within the low-velocity shear layers. The flame propagates as far upstream as where flame speed is equal to local velocity. Hot combustion products are recirculated back into the flame zone and aid stable combustion. So the combustion system geometry (specifically swirl angle and expansion ratio) have a direct impact on lean stability.

To broaden the range over which stable combustion can occur, several approaches are used in DLE systems. They may be used independently or in combination.

Fuel Staging

As previously mentioned a pilot fuel circuit can create hot stable combustion to help stabilize the overall lean primary zone. But this comes at the expense of higher NOx and should be minimized. A similar concept, known as staged combustion, can create two or more combustion zones where reactions can be fully premixed. Stage 1 is sized to achieve optimal temperature at low load receiving all the fuel flow. Stage 2 flows only air and exhaust products from stage 1 at low load. As load is increased, fuel is introduced to stage 2, resulting in stable combustion at very lean conditions due to the stabilization caused by mixing in exhaust products from stage 1.

Airflow modulation

Another approach to achieving desirable fuel/air ratio over wider load ranges is to divert air away from the combustion primary zone at low load. This can be achieved by simply dumping air overboard with a bleed valve mounted on the combustor case. When this approach is used, engine thermal efficiency (or heat rate) suffers as work is expended to compress air, which is dumped overboard without providing work through the turbine. Single-shaft machines can throttle the compressor inlet guide vanes to lower total engine airflow at low load and achieve the desired combustion fuel/air ratio with significantly less impact on thermal efficiency.

Variable Geometry

Several variable geometry approaches have been used to control flow splits between fuel injector and combustor liner over the load range. Restrictors or plugs can be installed at the fuel injector inlet to throttle airflow at low load. Variable position valves can be arranged to alter the pressure drop to the combustion liner and hence the airflow splits over the load range. Bypass valves can divert air around the entire combustion system and reintroduce flow upstream of the turbine. While all these approaches are excellent from a cycle efficiency standpoint, such systems can suffer durability concerns from continuous operation under high temperature conditions.

Pressure Oscillations / Dynamics

Combustion involves inherently unsteady processes. Swirler vortex breakdown, turbulence, and heat release are all unsteady or time dependent phenomena. Unsteady heat release leads to unsteady density and pressure. If the pressure fluctuations are amplified, enough energy can be present in the system to cause hardware damage to the combustion system and surrounding components. In a diffusion flame system, there exists great heterogeneity of fuel air ratio through the primary combustion zone volume. This leads to temperature spikes and pressure spikes that are randomly distributed and normally only generate low levels of acoustic energy as they cancel each other out.

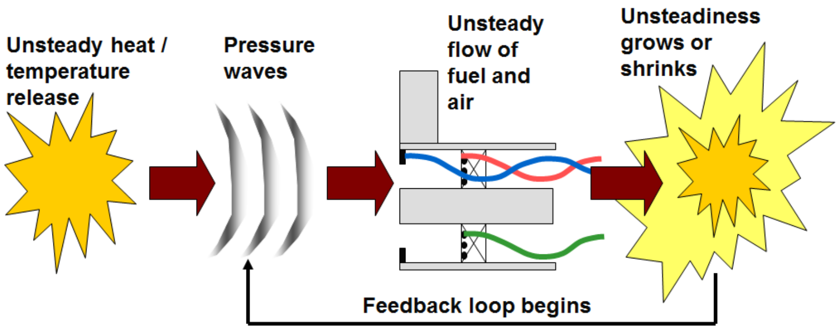


Figure 8. Combustion Pressure Oscillations or Dynamics Can Build if the Rayleigh Criterion is Met.

Recall that to minimize NOx, a DLE system strives for perfect premixing. In a well-mixed, homogenous system, all the heat release happens at very-nearly the same temperature. Any disturbance to the system can then be amplified by a uniform rise or fall in temperature and pressure throughout the flame zone (see figure 8). Since a DLE combustion system uses less wall cooling, the acoustic boundaries are hard and provide little damping. The reflection of the pressure fluctuations back to the fuel injector can cause a periodic rise and fall of fuel/air ratio, which in turn causes the heat release to fluctuate periodically. If the feedback loop becomes in phase, the pressure fluctuations are amplified and damage may occur. If the feedback loop is out of phase, then the system is damped and no damage occurs. This requirement for feedback to be in-phase for amplitudes to rise is referred to as the Rayleigh criterion.

It is very easy to predict the frequency of the system response, knowing the system dimensions and temperatures. Predicting the amplitude of the dynamics is much harder to do a priori. Flame location, stiffness of the fuel system, and natural system damping all come into play. Adjusting hardware dimensions can change the system response, getting the feedback out of phase and quieting the system. But since a gas turbine operates over a range of loads, ambient temperatures, and with a variety of fuels, it can be difficult to avoid worrisome acoustic amplitudes under all conditions. Solving this problem has become the single biggest technical challenge for the designers of DLE combustion systems.

Unfortunately, the easy solutions often lead to compromises in one of the other key performance parameters. Raising the amount of pilot fuel, reducing air to the primary zone, or intentionally causing the premixing to degrade have all been successful at reducing oscillations amplitudes – and increasing NOx. Increasing the amount of cooling air to enter the combustion primary zone helps damp the pressure reflections from liner walls, but also leads to compromises in turndown stability and/or CO emissions.

While several approaches exist to tune systems, or damp them from destructive dynamic pressure fluctuations, many of the techniques are kept proprietary to the OEMs. Steele and Cowell (1999) published one technique where the location of fuel injection was altered to break the feedback loop. Rawlins (1995) demonstrated that a change in premixer geometry could similarly impact the transport time in the fuel injector and hence break the feedback loop. Others have demonstrated actively pulsing a small amount of fuel out of phase with the oscillations can provide active damping. Still others have demonstrated adaptive control systems that adjust parameters such as fuel splits or air splits when dynamic activity is measured. Passive dampers, such as the resonators attached to a combustion liner in figure 9, have also been employed with success.

Figure 9. Combustion Liner with Helmholtz Resonators for Damping Pressure Oscillations.

Flashback/Autoignition

The fuel injector in a DLE system must thoroughly mix the fuel and air prior to combustion downstream. Since a flammable fuel/air mixture exists within the fuel injector, combustion there is also possible. If conditions allow the local fluid velocity to drop below the flame speed, the flame can travel upstream into the fuel injector. If the fuel injector contains areas with low velocity the flame can anchor inside the fuel injector and cause damage. This movement of the flame back into the fuel injector is referred to as flashback and must be avoided. While it is theoretically possible to upgrade injector materials and provide active cooling so a fuel injector can survive a flashback unscathed, holding a flame within the premixer allows it to burn at elevated temperatures and NOx, so must be avoided entirely.

Another phenomenon, known as autoignition, or spontaneous emission, occurs when a flammable fuel/air mixture starts the combustion process without an external ignition source. Researchers have correlated spontaneous ignition temperatures (minimum temperature where ignition can occur) and autoignition delay times (time required for significant reaction to proceed as to cause a rapid rise in temperature) for a variety of fuels and conditions. Autoignition is generally more likely when:

- The fuel is heavy, as breaking the chemical bonds in the fuel becomes easier
- Pressure is elevated
- Inlet temperature is elevated
- Residence times are long

Autoignition is generally not a problem for pipeline quality natural gas, but can become a concern for raw natural gas with elevated concentrations of heavier gaseous hydrocarbons. Liquid fuels have a much shorter autoignition delay time, so premixing length must be minimized for liquid-fueled DLE systems. Likewise lube oil, natural gas liquids, and other contaminants must be removed prior to feeding gaseous fuels to the engine. Coalescing filters are effective at removing these.

DIFFUSION-FLAME-COMBUSTORS

As mentioned in the introduction, the traditional combustion system for gas turbines has employed diffusion flame combustion. Diffusion flames are what we are accustomed to seeing around us. Burning occurs where the fuel meets the air at the appropriate mixture strength. The resulting flames are high temperature, which helps ensure additional reactants have plenty of thermal input for continuous combustion. Air is introduced into the combustion system gradually, allowing primary zone peak temperatures to exceed 4000ºF (2500K). The peak temperature, also called adiabatic flame temperature, is a function of fuel composition, inlet temperature and pressure. So higher pressure ratio engines also have higher peak flame temperatures and higher NOx. Typical NOx emissions from conventional combustion gas turbines ranges from about 100 ppm to about 400 ppm for natural gas fuel.

Several techniques exist to reduce NOx emissions from a conventional combustion system.

Water Injection for NOx Control

One of the most common techniques introduces water to the primary zone of the conventional combustor. The water directly reduces flame temperature and hence NOx. It is normally introduced through the fuel injector, either in dedicated passages or premixed with the fuel outside the engine. There is a limit to how much water can be introduced before flame stability is unacceptably compromised. Water/fuel ratios of 1:1 are typical and can reduce NOx from several hundred ppm down to 25-50 ppm. The water must be pure to avoid unacceptable fouling of fuel injectors or deposits on turbine blades and vanes. Hence a water-injected diffusion flame system has un undesirable impact on operating expenses. The lower temperature can also have a negative impact on CO emissions. Water injection does increase engine power.

Lean Direct Injection

Additional air can be allocated to the combustor primary zone. When introduced through the fuel injector, it is referred to as lean-direct injection. When introduced through the combustor walls, it is simply a lean primary zone. While combustion will still occur near adiabatic flame temperature, the overall temperature in the zone is reduced. Since thermal NOx formation is residence-time dependent, less NOx is produced as the time at peak temperature is minimized. While NOx reductions can be realized, levels achieved with water injection are not possible.

Exhaust Cleanup Systems

Several techniques exist to reduce NOx from the gas turbine exhaust, regardless of the combustion system type or whether measures have already been taken to reduce NOx formation within the combustion system itself. The most popular technique in use today is Selective Catalytic Reduction (SCR). Ammonia (NH3) or urea is injected into the exhaust upstream of a catalyst. Within the catalyst, the ammonia reduces NOx back to N2 and O2.

Since 90% reduction in NOx is achievable, SCR systems are used extensively in regions with poor air quality or stringent regulations. The system can reduce emissions from conventional engines down to 10-50 ppm, making them NOx competitive with untreated DLE systems. DLE systems combined with SCR can deliver NOx as low as 1-3 ppm.

SCR systems come with drawbacks. Initial capital expenses are high, catalysts must be replaced, and operating expenses with continuous ammonia use are also significant. Ammonia is a hazardous pollutant, so handling and storage are a concern. Ammonia slip in the exhaust must also be minimized for both regulatory and economic concerns. Sophisticated controls systems are required to monitor engine operation and downstream NOx concentrations and adjust ammonia flow appropriately.

DLE DESIGNS AND IMPROVEMENTS

The basic layout of a DLE system is shown in figures 1 and 3. Fuel injectors are large to premix fuel and air prior to combustion, reducing flame temperature and NOx. Combustors are large to allow full CO burnout at the lower temperatures. Additional pilot fuel circuits are used to aid stability at part load and during load transients. Additional engine controls are required to adjust airflow to the combustion system to maintain ideal conditions for NOx and stability at all loads.

Progress has been made in all aspects of the DLE system since introduction in the early 1990s. Originally released with 42 ppm NOx warrantees, engines have been offered at 25 ppm and 15 ppm NOx as the technology evolved. Many OEMs today offer their latest DLE combustion systems with single digit (9 ppm or less) NOx capabilities. The following refinements have made this possible.

Fuel Injectors

Fuel injectors at various OEMS vary significantly. All of them use swirl to both premix fuel and air and to establish the vortex breakdown for flame stability. The devices for generating swirl vary from axial-inflow swirlers, radial-inflow swirlers, compound angle swirlers, and slots or tubes that inject air tangentially. Fuel is injected at or near the air swirler and allowed sufficient time to premix, typically 1-2 milliseconds.

Many of the improvements in fuel injectors get back to improving upon the five topics discussed in the fundamentals sections. Mixing is improved for lower NOx. Aerodynamics are improved to enhance lean turndown and also avoid flashback. Designs are updated to minimize the production of harmful combustion pressure oscillations. Air used to cool injector tips is reduced to aid stability and reduce CO quenching.

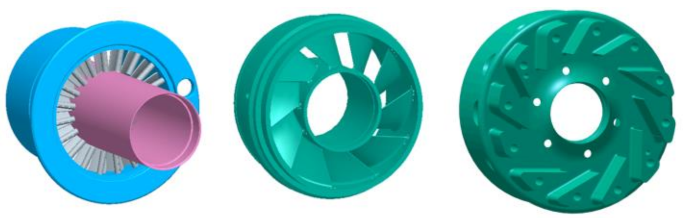


Figure 10. Fuel Injector Swirler Advancements from Fabricated Assembly to Casting to Fully Machined.

Additional improvements come from manufacturing processes, that allow for tighter tolerances and reduced production costs. Figure 10 shows how early fuel injectors were fabricated assemblies of several stamped sheet metal swirler vanes and gas injection tubes. These have been replaced by single piece castings with integrated fuel passages. This provides much improved control over tolerances and repeatable fabrication. It also allows for tailored swirler geometries and downstream flow field improvements not available with the simple sheet metal swirlers. Even tighter tolerances can be held by fully machining the swirler. As additive manufacturing techniques improve, additional design flexibility is available and tolerances can potentially be improved beyond that of the casting process.

Newer fuel injectors, with cleaner aerodynamics and improved repeatability are more fuel flexible. Heavy gaseous fuels with shorter ignition delay times and higher flame speeds can be tolerated as autoignition and flashback have been addressed.

OEMs today are working to improve designs to accommodate fuels with high concentrations of hydrogen. These fuels tend to have high flame speeds and wide flammability range. Hydrogen is interesting, since it is considered a green fuel. When excess renewable solar or wind energy is available, water can be electrolyzed to form hydrogen, which can then be burned directly or as mixed with natural gas.

Combustion Liners

The combustion liner contains the combustion process. The overall configuration of combustor liners varies. A can or can-annular configuration is common where multiple cylindrical combustion liners are fitted with one or more fuel injector per can. When arranged as external cans, the individual combustors can be readily removed from the engine for inspection or repairs. An annular configuration, shown in figure 1 is ubiquitous on modern flight engines and is also used on some industrial gas turbines. It has the advantage of maximizing the combustion volume with minimal liner surface area to cool. Multiple fuel injectors are arranged at the head end, or dome, of the annular liner.

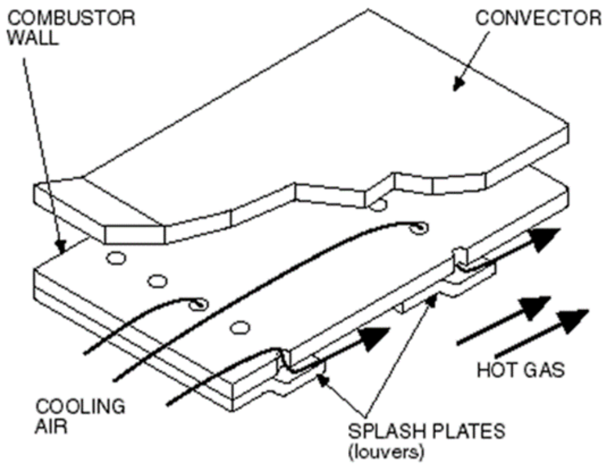


Figure 11. Film Cooling of Combustor Liner Walls (Greenwood, 2000).

Early conventional and DLE combustors were cooled with a technique known as film cooling. The approach, shown in figure 11, lays down a film of cool air between the hot combustion gases and the metal combustor wall. With distance, the film degrades and mixes with combustion gases, so additional cooling air must be provided. Several construction techniques are available, but simple louvers are common. While effective at keeping hot gas away from the walls, liners utilizing this cooling technique often suffer from temperature gradients with cold spots near air injection and hot spots further downstream as the cooling effectiveness degrades.

More efficient means of cooling liner walls is needed for three reasons:

- To allow more air to flow to the fuel injectors and reduce Tpz for reduced NOx
- To minimize the amount of cold air entering the primary zone of the combustor, aiding combustion stability
- To minimize the amount of cold air entering the primary zone of the combustor, to reduce CO quenching

Effusion cooling (figure 12) replaces the louvers with a large array of small diameter cooling holes. The cooling air removes heat as it passes though the effusion holes, then provides an even film on the hot side of the liner wall. These holes can be arranged to provide extra cooling where hot combustion gases impinge on the wall. Heat transfer can be further enhanced by providing an impingement shield with jets of air that first provide backside cooling to the hot liner wall.

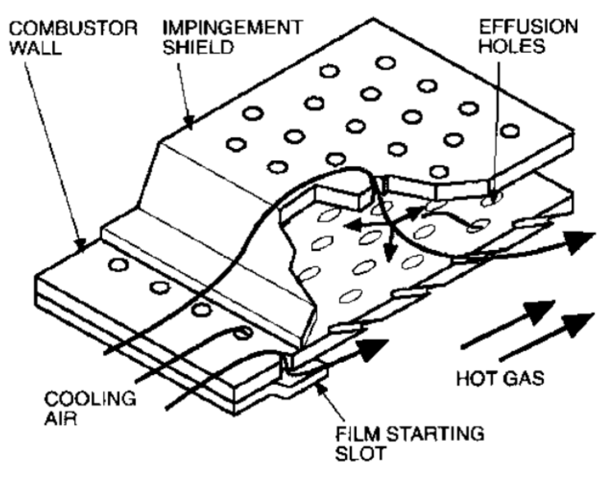


Figure 12. Impingement/Effusion Cooling of Combustor Liner Walls (Greenwood, 2000).

Many modern DLE combustors provide all liner wall cooling via backside cooling, where no cooling air enters the primary zone. The effusion holes in figure 12 are eliminated and backside impingement air alone does the work. After providing backside cooling to the primary zone of the combustor, the cooling air then flows downstream and enters the combustor as either exit cone cooling air or dilution/trim air. In some arrangements, trip strips or pin fins on the back of the hot liner wall further augment heat transfer. Effusion-cooled liners and impingement cooled liners tend to have smaller temperature gradients, which enhances life.

Figure 5 showed the tradeoff between NOx and CO emissions. Figure 13 shows how this changes as backside cooled liners are introduced. By eliminating the cooling air that enters the primary zone, onset of CO rise is moved to lower temperatures. This allows operation at lower temperatures for lower NOx without causing CO rise.

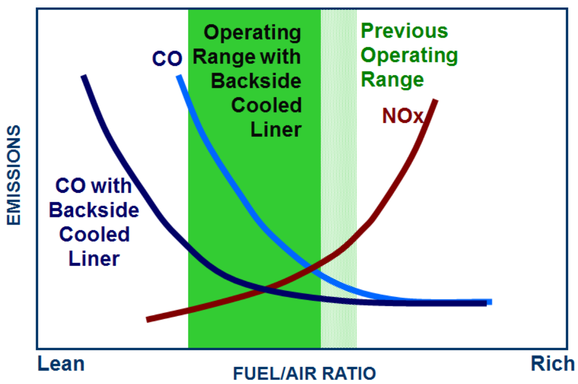


Figure 13. Lower NOx and CO are Possible with Backside Cooled Liners.

As turbine firing temperatures rise and approach DLE primary zone temperatures, very little air is left over for liner cooling or combustor exit temperature profile trim. Serial cooled liners are one answer, where the air does double duty. See figure 14. Air first cools the liner walls, then some flows forward to the feed the fuel injectors, while the rest flows aft to cool the liner exit and trim exit temperature profile. This has the double advantage of allowing more air to cool the liner walls and also warming up the air before it enters the combustor, aiding stability and allowing operation at even lower primary zone temperatures. Hence lower NOx is also possible. More pressure drop may be required, having a small negative impact on overall engine thermal efficiency. Recent publications such as Lindeman, et al. (2014) and Huitenga and Norster (2014) show that serial cooling is becoming more common for new DLE combustion systems.

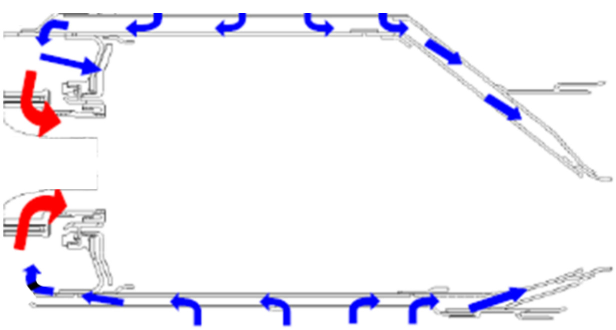


Figure 14. Serial Cooled Combustor.

Fuel Systems and Controls
Care must be taken to properly monitor and control the engine to ensure the combustion system stays in the desired operating range; as lean as possible, but with sufficient margin above lean extinction, as shown in figure 6. Controlling overall fuel flow to the engine is already a requirement for stable engine speed and turbine inlet temperature. But controlling the split of fuel between main fuel and pilot fuel becomes very important for the combustion system performance. Desired fuel splits are achieved with high-turndown fuel control valves, activated with high force and quick-response electric actuators. Improved algorithms control the total fuel flow with greater steadiness to engine degradation and fluctuations in fuel heating value or pressure.

Airflow to the combustor is controlled by overboard bleed or compressor inlet guide vanes. Older hydraulic actuation is replaced by high-force and quick response electric actuators. Improved algorithms manage engine airflow by managing the airflow based on calculated primary zone temperature, rather than the directly measured turbine inter-stage temperature.

Monitoring for combustion dynamic pressure has improved over time. Dynamic pressure transducers detect the pressure fluctuations, then the signal is processed and analyzed. Low temperature transducers have been replaced by high temperature sensors, allowing the transducer to be mounted directly to the engine and improving the signal quality. Band-pass filters have been displaced with Fast-Fourier Transform algorithms to determine full frequency and amplitude information. More capable engine PLCs (programable logic controllers) are making possible more sophisticated controls logic in response to measured combustion dynamics.

ADVANCEMNETS IN ANALYSIS

One of the main tools for the gas turbine combustion engineer is CFD (Computational Fluid Dynamics). This numerical analysis tool breaks up a volume into a mesh of discrete cells and then solves a series of simultaneous equations to describe the fluid at each location. In its simplest form, CFD solves the Navier-Stokes equations for conservation of mass, momentum, and energy at each cell in the mesh. In doing so, it can resolve key parameters of interest such as fluid temperature, pressure, and fluid velocity at each location. Additional equations can be included to determine species concentrations and phase. Chemical kinetics can be introduced to track progress of chemical reactions at each location. Spray models can be incorporated to track liquid fuel breakup, atomization, and evaporation.

Boundary conditions must be supplied to the CFD model to describe the known or assumed conditions at the inlet(s) and outlet(s) of the control volume to be solved. The code then iteratively solves for all the variables of interest at every cell in the grid. The calculated error between the currently assumed properties and that required by the equations is evaluated for each iteration. For a well-behaved system, this error, or residual, eventually diminishes and the solution is said to converge once the residual is small enough. A more detailed description of CFD is out of scope for this paper, but a nice introduction to the technique is provided by Sorokes, et al. (2017).

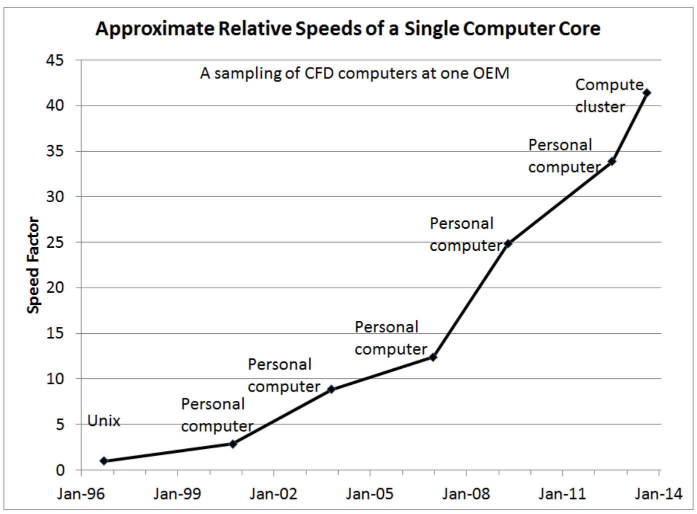


Figure 15. Speed of a Single Computer Core Through History. (Courtesy of J. Hardin, The Elliott Group)

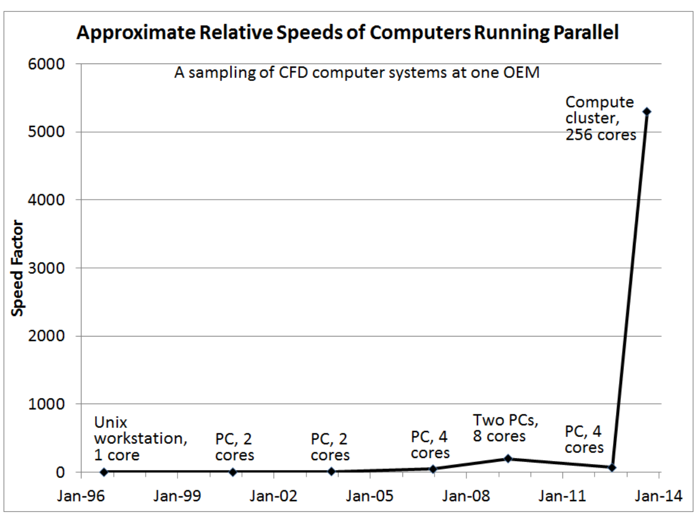


Figure 16. Speed Increase with Multiple Cores. (Courtesy of J. Hardin, The Elliott Group)

All of this takes significant computing power to solve a large number of equations for a large number of discrete cells within a grid. It is no surprise then that as computers have gained in speed and memory, ever larger CFD models can be solved. Figure 15 shows the incremental increase of computing power over the past 20 years. More recently, CPU cores have been placed in parallel and a step change in computing capabilities has resulted (see figure 16). It is reported that a nearly linear speed up results from the additional cores (Sorokes, 2017). A typical CFD job at my company would currently employ 200-300 cores and see an over 200-fold increase in computational power vs the single core machine. This has allowed the engineer to further refine or expand the models to gain even better insights to the flow behavior.

Models have expanded from simple 1-D models in the early days to simple 2-D axisymmetric models. These might still be used in the conceptual design phase, but 3-D models are now the standard for resolving flow.

The models are getting bigger. More refined meshes allow for greater detail and precision in resolving local features. Where effusion cooling may have once been modeled as a wall with a given flux of cooling air, now each of the individual holes can be modeled explicitly, with better results.

The scope of the models is expanding. Common practice in the 1990s was to break up the physical space into several distinct regions for modelling. So a model of a fuel injector premixer would assume boundary conditions upstream of the injector inlet and downstream of the injector exit. A compressor diffuser model would only treat the fuel injectors as a sink for flow. A separate model would treat the fuel manifolds and piping to the fuel injector. Another model might examine the combustion space. Now all those components can be combined into a single CFD model (see figure 17). There are fewer boundaries to assume and the interactions between components are now solved explicitly. Such an expansive CFD model today might have as many as 70 million nodes in the mesh.

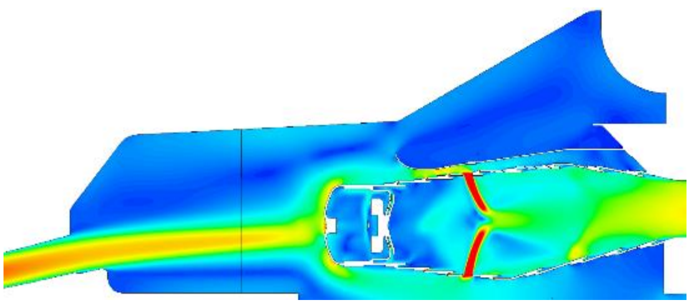


Figure 17. CFD Resolved Velocity Profile of a Conventional Diffusion Flame Combustion System, Indicating Interactions of Compressor Diffuser, Fuel Injector, Combustor, and Dilution zone.

Older CFD models may have assumed conditions known not to be true – such as the inlet to the fuel injector is identical at each of the fuel injectors in an engine. A periodic boundary condition was assumed between injectors. Much improved results are obtained when multiple neighboring injectors are modeled together. The resulting CFD solution shows the interaction of diffuser struts, liner support pins and other local features on the flow within each fuel injector. Since perfect mixing of fuel and air is the ideal state for a DLE system, it is very helpful to understand the differences in performance of identical injectors placed at different locations within the engine.

Chemical reactions can now be modeled more explicitly. Once upon a time, the combustion engineer would settle for solving CFD models for cold flow conditions or model simple two-step reactions. Now reacting CFD models can determine flame front location and temperature profiles with good agreement to empirical measurements. But even today's most capable CFD models are not capable of fully resolving flow and also assessing the hundreds of chemical reactions known to occur with hydrocarbon combustion. But the old standards of two-step or four-step reactions are giving way to more detailed modeling of the combustion processes with a lookup reaction chemistry table that is derived from the full chemistry. This gives better resolution of temperature and species history, which can give insights to the generation of pollutant emissions of NO, CO, and UHC.

Conjugate heat transfer analyses can now be performed with increasing confidence. Where combustor wall temperatures were once calculated with separate heat transfer codes, it can all be done with practically useful accuracy with CFD. Since CFD has already resolved fluid composition, temperature and velocity near the combustor walls, heat transfer process can be modeled accurately to determine temperatures at the wall surface and even throughout the thickness of the combustor walls, accounting for conduction, convection and radiation. Figure 18 is an example of a conventional combustor with calculated surface temperatures. Again, greater confidence is gained that the predictions will represent actual combustion system performance, so problems can be identified and addressed prior to any prototype hardware fabrication and testing.

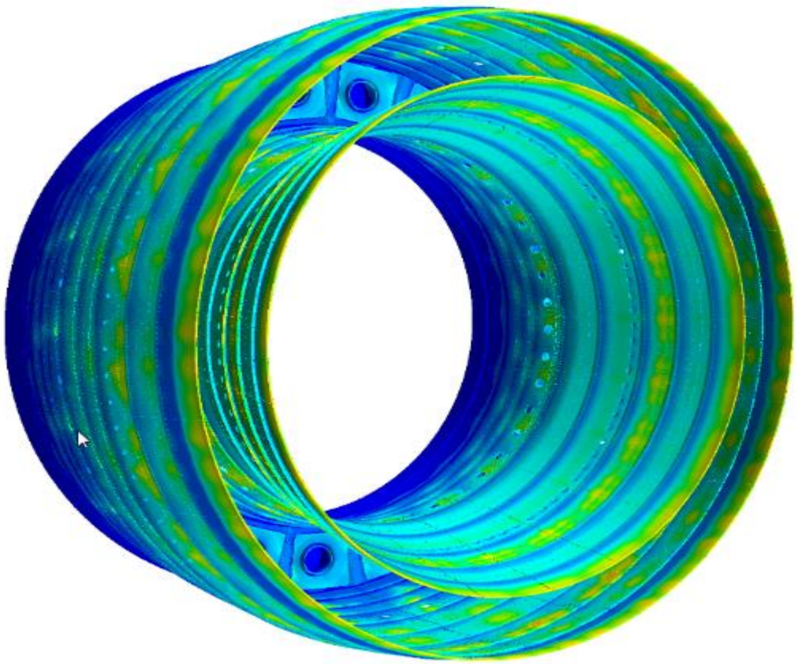


Figure 18. Conjugate Heat Transfer Results, Indicating Liner Wall Temperatures.

The combustion process involves significant temperature gradients, large-scale flow reversals, and small-scale turbulence. Achieving a steady state solution is sometimes acceptable. Turbulence models have been developed over time to account for the diffusion and mixing of flows due to very small-scale interactions. The RANS (Reynolds-Averaged Navier-Stokes) technique is good for a quick assessment or design sensitivity study. While an improvement over laminar flow simulations with turbulence models, it does not resolve large unsteady turbulence accurately. The Large Eddy Simulation (LES) technique resolves the large-scale turbulence over discrete time steps, achieving a more accurate time-resolved solution. While significantly more time-consuming (expensive), the LES technique can provide improved accuracy, especially when modelling a final configuration. Figure 19 shows the LES flow solution with small and large-scale turbulence in a DLE combustor. Figure 20 shows how LES provides a more accurate prediction of combustor exit temperature profile than RANS, when compared against rig data.

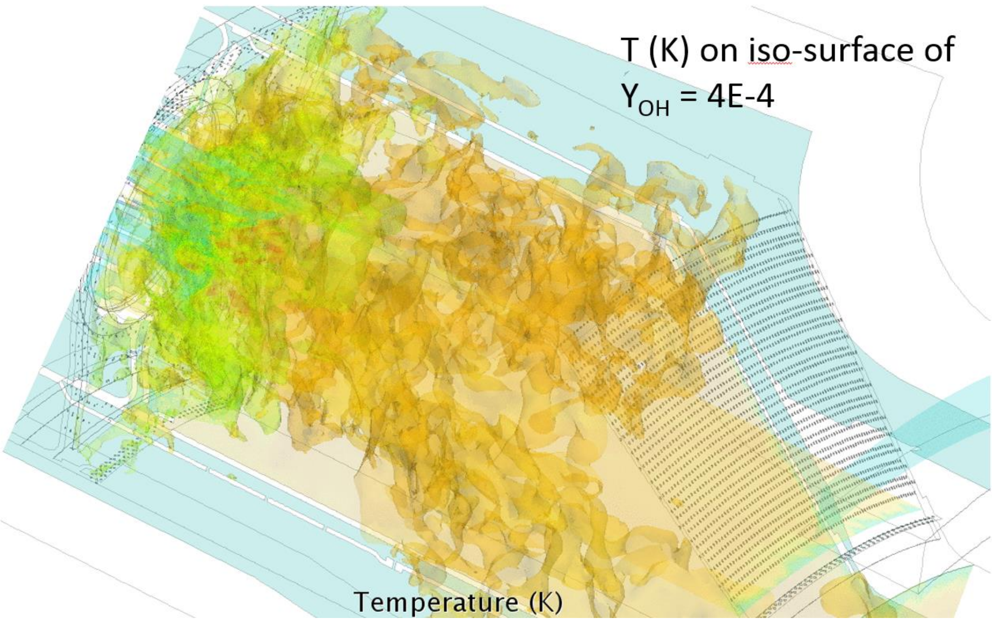


Figure 19. LES Time-Resolved Solution of Combustion Primary Zone, Indicating Local Temperatures on Turbulent Reacting Flow.

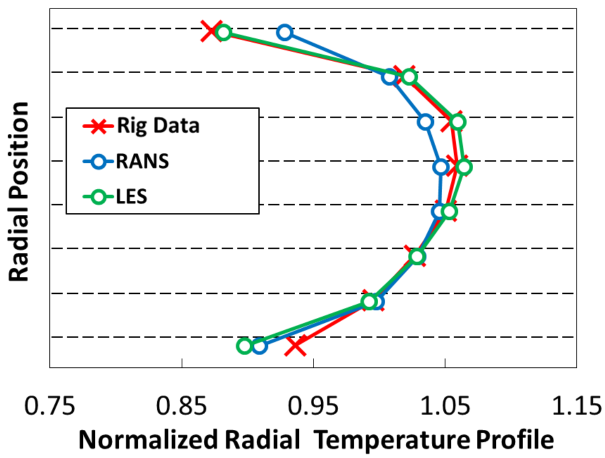


Figure 20. Combustor Exit Temperature Profile, Comparing Rig Data with CFD Prediction. RANS Overpredicts Mixing, while LES Solution is Very Close to Empirical Data.

The increased computational capability is also enhancing ability for finer mesh mechanical stress and life predictions. Sophisticated combustion dynamics simulations are also developing, allowing better prediction of acoustic behavior early in the design process. High fidelity CAD models are also allowing for use of evolving manufacturing techniques. Design optimization codes are tying together the geometry changes in CAD with updated CFD flow results and structural analysis to identify optimum configurations.

ADDITIVE MANUFACTURING

Many material forming techniques are available to turn concepts into hardware. Traditional machining of wrought bar stock or plate is extensively used to manufacture fuel injector and combustor details. Non-traditional machining techniques such as EDM (Electric Discharge Machining), laser drilling, and water-jet drilling allow for precision forming of small features, such as combustor cooling holes. Casting and forging are cost-saving ways to achieve near-net shapes when production quantities justify the cost of tooling.

The advent of additive manufacturing (sometimes referred to as 3-D printing) has been a game-changer. Several processes exist that build up parts layer by small layer into complex structures. Early techniques could manufacture prototype parts and display pieces out of various plastic or composite materials. Today, production-worthy metal parts can be produced. In powder-bed additive manufacturing, a thin layer of powder is laid upon a base plate. A laser passes over the powder bed selectively heating up the powder to liquid form, which then solidifies into the desired shape. Another thin layer of powder is applied and the laser builds up another layer of solidified powder on top of the last. When the process is completed, excess powder is removed and the parts are cut from the base plate, see figure 21. Other processes use wire feed to build up the structure. The resulting parts appear under the microscope as one large weld in the shape of the finished part.

Figure 21. Additive Manufactured Fuel Injectors on Base Plate.

Significant efforts have been made by industry to develop the additive manufacturing techniques. Machines with multiple lasers promise ever faster part production. Refinements in machine design and controls logic lead to more uniform powder distribution, laser power, and ultimately better finished parts. Materials development has produced more uniform powders and a wider range of alloys are available. Research is better defining finished material properties, which are different from traditional wrought or cast parts. Improvements in quality control and part post-processing are helping achieve more uniform parts.

All this technology affords several advantages to the combustion engineer. Prototype parts can be built much quicker and features can be quickly iterated and retested. Alternately, one build plate can contain several slightly different designs that can then be evaluated. This speeds up the design process.

Design features and shapes can now be produced that would be impossible or very difficult with traditional methods. Complex geometries are no more expensive to manufacture than simple ones, allowing design flexibility. The aerospace industry is using this capability to take weight out of parts without compromising strength. The industrial gas turbine benefits by allowing for more insulating cavities between cold fuel on one side and hot combustion on the other. The industrial engine also benefits by more streamlined fuel passages without the abrupt corners and edges of traditional machining techniques. Some manufacturers are using the additive process to refurbish fuel injectors at overhaul, by salvaging the good parts and rebuilding the heat- or stress-damaged parts directly onto the existing injector.

MATERIALS TECHNOLOGY

Materials technology continues to evolve. Early gas turbine combustors were made with high temperature stainless steels, which could be expected to have reasonable life with peak temperatures near 1200ºF (920K). This has long been replaced by high-temperature nickel alloys such as Hastelloy X, Haynes 230, Inconel 600, and others. These metals can withstand continuous operation with peak temperatures above 1600ºF (1140K). Monolithic ceramic and ceramic matrix reinforced ceramic (CMC) combustion liners have been tested in the factory and the field. They hold the promise of enduring combustion temperatures with little to no cooling air. Van Roode, et al. (2007) reported a SiC/SiC ceramic combustion liner successfully completing over 67,000 operating hours in a fielded engine. But ceramic continues to have concerns for long term durability and shock resistance, particularly with the high temperature gradients of liquid-fueled combustion.

Thermal barrier coatings (tbc) represent a convenient compromise between the high temperature capability of ceramic and the toughness of metal. The metal wall has a bond coat applied to bridge the thermal conductivity difference between the metal substrate and the thin ceramic tbc layer. Tbc and bond coat are normally applied by plasma jet deposition. Temperature gradients of several hundred degrees F across the wall thickness are common and allow two benefits. First, the surface facing the flame can run hotter, decreasing the quenching effects on the chemical reactions, thus improving combustion stability. Second, less cooling air is required to keep the metal walls at acceptable temperatures for long life. Thus, more air can be premixed with the fuel for lower flame temperature (lower NOx) or for dilution zone trimming of the temperature entering the turbine (longer turbine life).

FUEL FLEXIBILITY AND TREATMENT

Gaseous Fuels

Gas turbines are inherently fuel-flexible machines. With continuous combustion and a stable combustor primary zone, many fuels may be introduced and burned completely and cleanly. Gaseous fuels ranging from pipeline quality natural gas to raw natural gas, associated gas, liquid petroleum gas (LPG), propane, butane, landfill gas, digester gas, refinery process gases, biomass, syngas, coke oven gas and other process waste gases have all been used successfully in gas turbines. Conventional combustion engines tend to be more fuel flexible than DLE engines, due to the concerns for flashback, autoignition, and combustion dynamics with the premixed DLE combustion systems.

Several parameters are useful in characterizing candidate fuels. For a gaseous fuel, Lower Heating Value (LHV), flammability limits, adiabatic flame temperature, dew point, flame speed, autoignition characteristics, and contaminant concentrations are important in determining fuel suitability. Wobbe Index relates the heating value and density of the fuel:

$$Wobbe\ Index = LHV / \sqrt{SG}$$

The Wobbe Index has units of Btu/scf or MJ/Nm^3 and is useful when comparing fuels of significantly different compositions. Two fuels with a given Wobbe Index will require the same pressure drop to provide the same energy output. A system designed for natural gas with a Wobbe Index near 1200 Btu/scf will take less pressure drop when burning propane (Wobbe Index closer to 1900 Btu/scf) and may require a smaller orifice size to achieve an acceptable pressure drop for proper fuel distribution between fuel injectors. Hence, a gas turbine may require fuel injectors with different effective areas to handle fuels of widely varying Wobbe Index. Fuel valve sizing will also be impacted by Wobbe Index.

Contaminants of concern for gaseous fuels include solids, water, lubricating oil, siloxanes (for landfill gas), and elemental sulfur. Compounds impacting safety, classification and system design include hydrogen sulfide (H2S), hydrogen, carbon monoxide and carbon dioxide. While solids and liquid contaminants can be removed by filtration, other constituents cannot be readily removed at the industrial gas turbine installation site.

Gaseous fuels must be kept in the gaseous state to avoid poor distribution. Hence fuels containing water or heavier hydrocarbons may require heating to keep the fuel acceptably above the dew point. Gas turbine OEMS provide guidance in their fuel specifications, and a superheat of 50ºF above dewpoint is typical. Coalescing filters are useful in removing any remaining liquids, including compressor lube oil. Since fuel temperature impacts density and hence Wobbe Index, a corrected Wobbe Index is used for determining system pressure drops and component sizing. Figure 22 shows an example of how fuel pressure and dewpoint change as the fuel progresses through the fuel system and how the 50ºF superheat keeps the fuel above dewpoint at all stations.

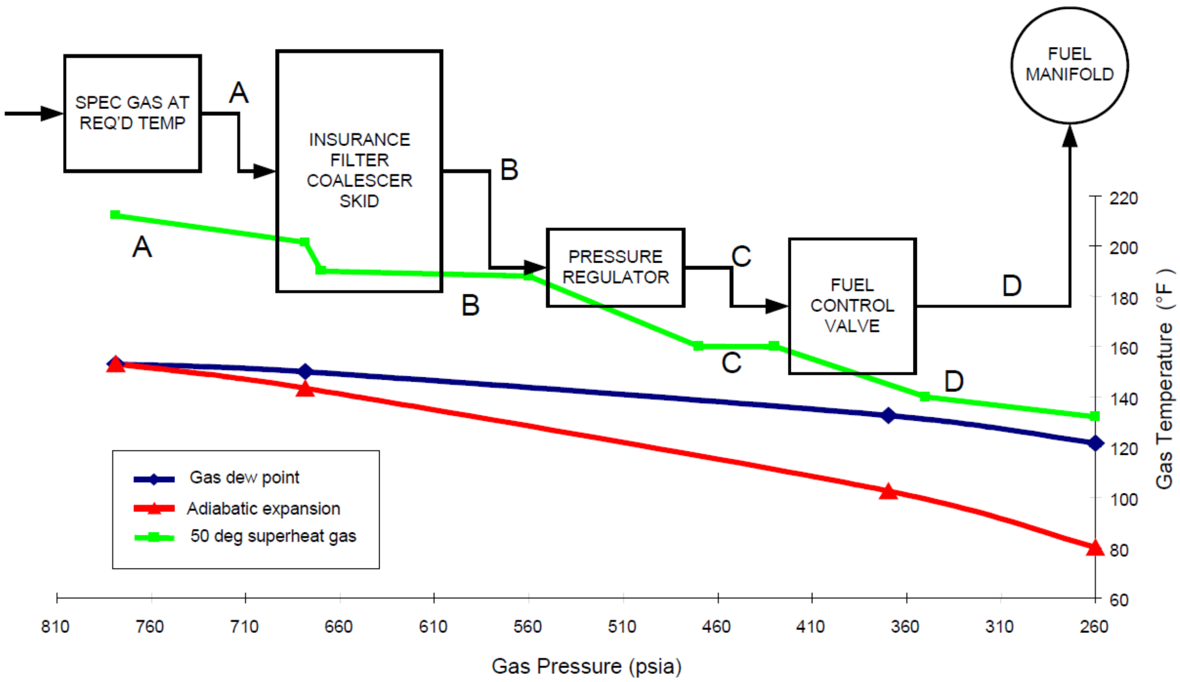


Figure 22. Superheat Temperature Requirements in a Typical Gas Turbien Fuel System.

When a raw natural gas fuel contains elevated levels of hydrogen sulfide (H_2S), it is said to be a sour gas. Due to the corrosive nature of H_2S on the turbine, OEMs place limits on its allowable concentration. The limits will depend on engine firing temperature, as hot corrosion is more severe in higher temperature engines. Mitigations, such as turbine blade coatings, are used to allow even very high concentrations of H_2S in some turbines. Unfortunately, H_2S removal is a refinery process and site reduction is not an option.

Elemental sulfur is found with some shale gas fuels. While elemental sulfur concentrations are usually quite low and not of concern for turbine corrosion, it can sublimate out and contaminate fuel valves, causing valve effective areas to decrease. Fortunately, this can be addressed through additional fuel heating to keep fuel valves clean and functioning.

Contaminants can enter a gas turbine with the fuel, but also with other fluids as shown in figure 23. To address this, OEMs specify allowable contaminants in Fuel Equivalent Concentrations (FEC), that include contaminants contained in the fuel, air, and water entering the engine.

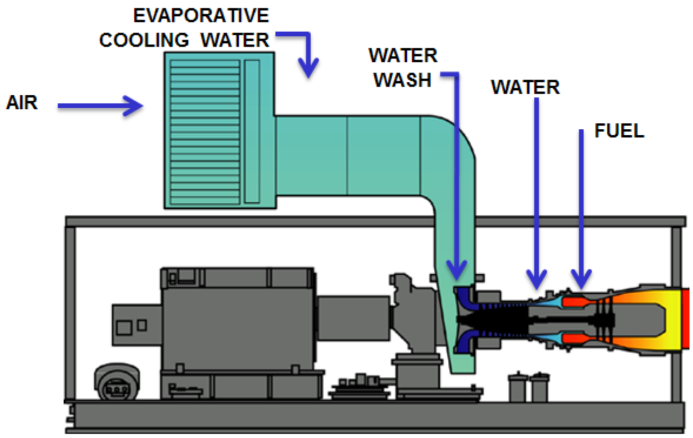


Figure 23. Gas turbine contaminant sources.

Liquid Fuels
A range of liquid fuels can be used in gas turbines as well. Diesel and kerosene fuels (including aviation fuels) are the most commonly used liquids, due to their ready availability and desirable physical and chemical properties. Other liquid fuels including LNG, natural gas liquids, naphtha, gasoline, biodiesel, marine diesels, and even light crude oils have been used with industrial gas turbines. The most important physical and chemical properties of a liquid fuel that impact its suitability include aromatic content, distillation, flash point, heating value (LHV), lubricity, olefins and diolefiins, Reid vapor pressure, specific gravity, and viscosity. OEMs provide guidelines on each of these properties to ensure acceptable operation of the engine. Liquid fuel contaminants of greatest interest include sulfur, nitrogen, solids, water, sodium, potassium, vanadium, and other metals. These contaminants can either foul the fuel system causing uneven burning, or attach the turbine and shorten life.

The sourcing and management of liquid fuels is key to successful engine operation. The refinery fractionates crude oil into various classifications of fuels, which can then be blended to meet the requirements of various fuel specifications. Additional refinery processes may be used to remove sulfur and other contaminants. For example, ASTM Specification D975 specifies various grades of diesel by sulfur levels, with “Grade No. 2-D S15” (formerly referred to as Ultra-Low Sulfur Diesel) containing 15 ppm sulfur (maximum).

While a liquid fuel may leave the refinery conforming to an industry fuel specification, the transportation and handling of the fuel can introduce contaminants. At site, filters and centrifuge can remove water, solids, and water-soluble contaminants. Contaminants such as sulfur and nitrogen cannot be removed on site. Liquid fuels can change properties in the holding tank as solids form, water condenses, or algae grows. Proper storage and handling of the fuel can prevent sludge from the bottom of the tank being introduced to the turbine, per figure 24.

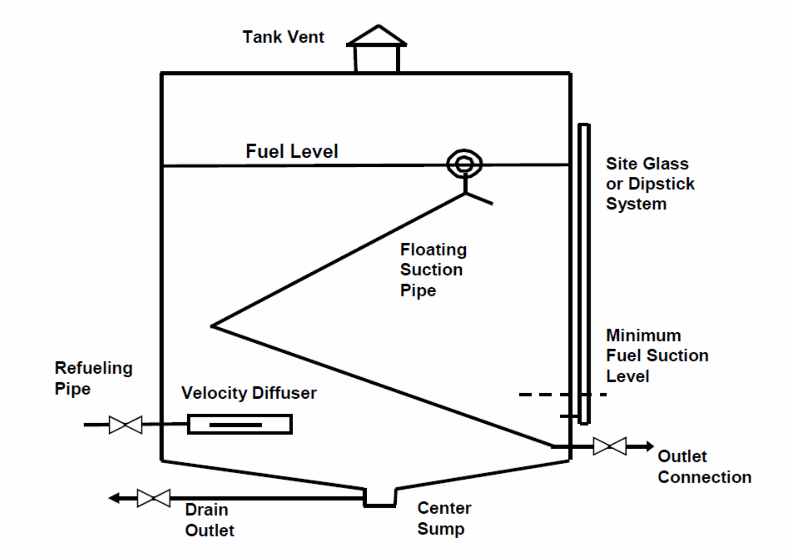


Figure 24. Schematicv of Gas Turbine Liquid Fuel Storage Tank.

CONCLUSIONS

The fundamental best practices for DLE system design are well established. Improvements in computing power, manufacturing technology, engine controls, and maturing design practices are leading to combustion systems that can achiever lower NOx and CO emission with greater fuel flexibility, durability, and life.

NOMENCLATURE

ASTM = American Society for Testing and Materials
BACT = Best Available Control Technology
CFD = Computational Fluid Dynamics
CH4 = Methane
CO = Carbon Monoxide
CO2 = Carbon Dioxide
DLE = Dry Low Emissions combustion system
DLN = Dry Low NOx combustion system
EDM = Electric Discharge Machining
EPA = Environmental Protection Agency
H2S = Hydrogen Sulfide
LAER = Lowest Achievable Emission Rate
LBO = Lean Blow Out
LES = Large Eddy Simulation
LHV = Lower Heating Value
LPG = Liquid Petroleum Gas (primarily propane and butane)
LSD = Low Sulfur Diesel
NO = Nitric Oxide
NO2 = Nitrogen Dioxide
NOx = Oxides of Nitrogen, specifically NO + NO2
NSPS = New Source Performance Standard
PLC = Programable Logic Controller
RANS = Reynolds-Averaged Navier-Stokes turbulence model
SCR = Selective Catalytic Reduction
SO2 = Sulfur Dioxide
tbc = Thermal Barrier Coating
UHC = Unburnt Hydrocarbons
ULSD = Ultra-Low Sulfur Diesel
VOC = Volatile Organic Compounds

REFERENCES

Fenimore, C. P., 1971, "Formation of Nitric Oxide in Premixed Hydrocarbon Flames," 13th Symposium (International) on Combustion, Combustion Institute, Pittsburgh, PA, pp. 378-380.

Greenwood, S., 2000, "Low Emission Combustion Technology for Stationary Gas Turbine Engines, *Proceedings of the 29th Turbomachinery Symposium*," pp.125-133.

Huitenga, H. and Norster, E. R., 2014, "Development Approach to the Dry Low Emission Combustion System of MAN Diesel & Turbo Gas Turbines," ASME Paper Number GT2014-25380, Proceedings of ASME Turbo Expo 2014: Turbine Technical Conference and Exposition.

Leonard, G. and Stegmaier, J., 1993, "Development of an Aeroderivative gas Turbine Dry Low Emissions Combustion System," ASME Paper Number 93-GT-288, International Gas Turbine and Aeroengine Congress and Exposition.

Lindeman, O., Andersson, M., Persson, M., and Muntell, E., 2014, "Development of a Liquid Fuel Combustion System for SGT-750," ASME Paper Number GT2014-25380, Proceedings of ASME Turbo Expo 2014: Turbine Technical Conference and Exposition.

Lovett, J. A. and Abuaf, N., 1992, "Emissions and Stability Caracteristics of Flameholders for Lean-Premixed Combustion," ASME Paper Number 92-GT-120, International Gas Turbine and Aeroengine Congress and Exposition.

Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura and H. Zhang, 2013: Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA (page 731).

Rawlins, D., 1995, "Dry Low Emissions: Improvements to the SoLoNOx Combustion System," Eleventh Symposium on Industrial Applications of Gas Turbines Canadian Gas Association, Banff, Alberta, Canada, October 1995.

Sorokes, J. M., Hardin, J., and Hutchinson, B., 2017, "A CFD Primer: What Do All Those Colors Really Mean?," 46th Turbomachinery & 33rd Pump Symposia, Houston, Texas.

Steele, R. and Cowell, L., 1999, "Passive Control of Combustion Instability in Lean Premixed Combustors," ASME Paper Number 99-GT-52, International Gas Turbine and Aeroengine Congress and Exposition.

Van Roode, M., Price, J., Kimmel, J., Miriyala, N., Leroux, D., Fahme, A., and Smith K., 2007, "Ceramic Matrix Composite Combustor Liners: A Summary of Field Evaluations." Journal of Engineering for Gas Turbines and Power, volume 129, pp. 21-30.

BIBLIOGRAPHY

D975-18, 2018, "Standard Specification for Diesel Fuel Oils," ASTM International, West Conshohocken PA, USA.

Davis, L. B., 1996, "Dry Low NOx Combustion Systems for GE Heavy-Duty Gas Turbines," ASME Paper Number 96-GT-27, International Gas Turbine and Aeroengine Congress and Exposition.

Lefebvre, A., 1983, *Gas Turbine Combustion*, Taylor & Francis publishers.

ACKNOWLEDGEMENTS

The author would like to acknowledge colleagues in the Combustion Engineering Department at Solar Turbines for their advice, hard work and contributions to the content and graphics in this paper.